Using 3-D MODFLOW to Predict Salt Movement Under Feedlot Holding Ponds.

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Abstract

MODFLOW was used as modeling tool to predict salt movement under three different types of feedlot waste storage ponds: a typical shallow holding pond with a clay liner, a deep unlined pit lagoon, and a shallow evaporation pond with a compacted clay liner. We found that the measured hydraulic parameters and the layer characterization of the underlying strata was not always an exact science. Nonetheless, once the model was calibrated and refined, the outcome appeared realistic.

Introduction

Seepage below feedlot holding ponds is of concern because of potential aquifer contamination. The amount of effluent runoff from a feedlot reaching holding ponds has been studied by a number of authors. One of the more recent intensive runoff studies was conducted by Alberta Agriculture (Kennedy et. al., 1999) at a feedlot located near Vegreville. This study found that runoff yields from various pens ranged from 22% to 74% depending upon the storm event and antecedent precipitation (according to the report some of the storms were 50-year storm events). Miller et. al. (2003) measured run-off yields from Lethbridge feedlots of only 5-45%. These authors concluded that the old standard of 76 mm (based on the 24 hr-25 yr storm) was too excessive. Maule and Fonstad (2007) conducted a runoff study for Saskatchewan using long-term climatic records, laboratory studies and the results of Millar's work on three Alberta feedlots to predict feedlot runoff. They concluded that sizing ponds based on the 24 hr-25 yr storm is far too great, even too great for the 1:100 year storm.

Olson et. al. (2005) measured groundwater chemistry under newly constructed feedlots at Lethbridge and found that over a period of 4 years, Cl had increased in the wells within the pens, but not outside the pens. Both McCullough et. al. (2001) and Miller et. al. (2007) examined the effect of texture on nutrient movement beneath feedlot pens and both concluded that soil texture had little impact as cattle packing of the feedlot floor in conjunction with infiltration of bacteria and organic matter caused plugging and self-sealing similar to that reported for catch basins (Parker et. al., 1999 a, b).

Methodology

The feedlots being studied by Normac were located about 5 km south of the City of Moose Jaw (Figure 1). The Main Feedlot is located on SE32-15-26W2 just west of the north-south Highway No. 2 and the West Feedlot is located on NH31-15-26W2, approximately 1.6 km (1 mile) westnorthwest of the Main Feedlot. In each feedlot, the South Central Cattle Company wanted to expand from approximately 2,500 head to 6,000 head.

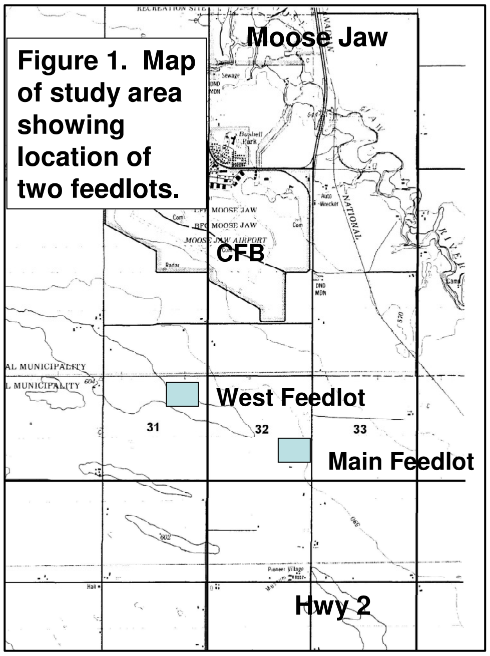


Figure 1. Map of study area showing location of two feedlots.

In our study we used MODFLOW to simulate seepage below a feedlot holding pond. MODFLOW is a finite-difference numerical groundwater model that uses Darcy's Law and the principle of conservation of fluid mass to predict groundwater flow and solute transport. It is a tool that can be used to provide a simplified representative of the real groundwater flow system. Over time, the model has been modified, improved and has been made more user friendly. The model of choice today is Visual MODFLOW which was originally developed by the University of Waterloo and is now being supported by Waterloo Hydrologic, Inc (2006), a Schlumberger Water Services company.

MODFLOW was used as the modeling tool to predict salt movement under three different types of feedlot waste storage ponds: shallow unlined, deep unlined and a shallow evaporation pond with a clay liner.

Results

Scenario 1: Main Feedlot—Typical holding ponds

The "model domain" selected for this study was a rectangular shape 1000 m wide and 2000 m long starting on the west side of the Main feedlot and traversing across Highway 2 to the northeast in a downslope direction (see Figure 2). The X-Y grid spacing varied from less than 2 m near the holding ponds to about 20 m east of the containment ponds.

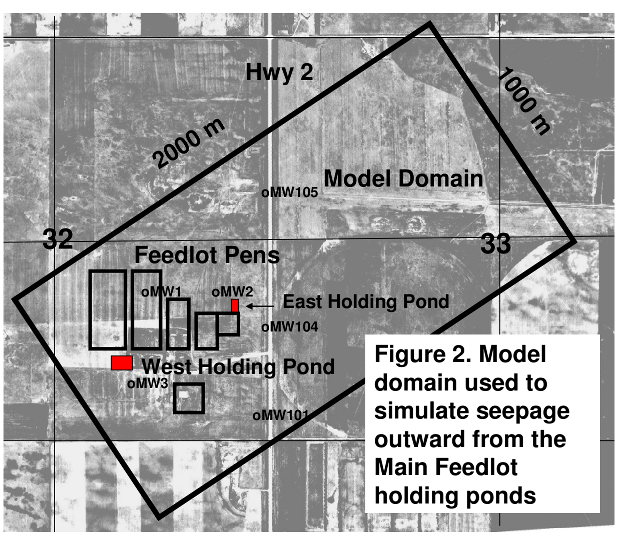


Figure 2. Model domain used to simulate seepage outward from the Main Feedlot holding ponds

Land elevations were extrapolated from the Main Feedlot survey and from the topographic map for the land areas across Highway 2 east of the feedlot. Three layers were defined in the Z direction (vertical) (Figure 3). The surface layer (about 14 m deep) was assigned hydraulic conductivities of 1E-5 m/sec (315 m/yr) in the horizontal directions (x and y) and 1E-6 m/sec (31.5 m/yr) in the vertical direction (z). Usually, hydraulic conductivities are about 10X higher in a lateral direction than in a downward direction. The hydraulic conductivities input for the surface layer was based on the soil measurements and extrapolating these to the strata below the containment ponds. The x-y hydraulic conductivities of the deeper clay till layers were measured using piezometer recovery tests and were 1E-6 and 1-E-7 m/sec.

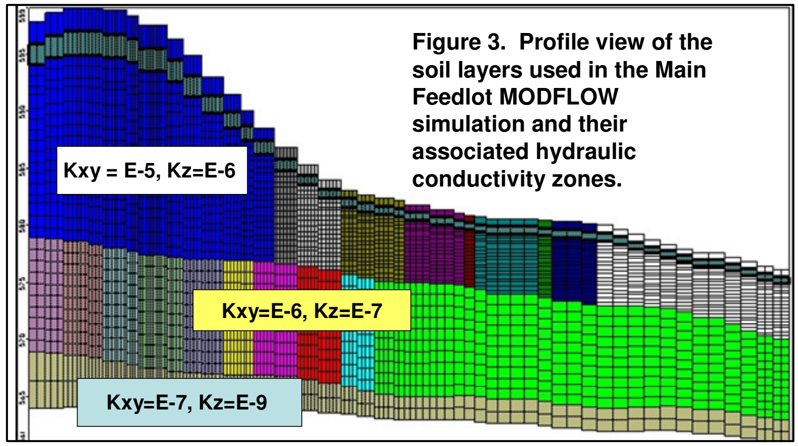


Figure 3. Profile view of the soil layers used in the Main Feedlot MODFLOW simulation and their associated hydraulic conductivity zones.

Based on the hydraulic conductivity measurements of the clay till underlying the holding ponds, it was calculated that a recharge rate of about 100 mm/year might be expected from each of the holding ponds. This would require packing of the underlying clay and sealing by fine organic and clay particles such that an hydraulic conductivity of 3E-9 m/sec or less could be achieved. The hydraulic K measurements on the underlying clay till layer and visual observations at the feedlots of ponded water at depth would indicate that a seepage rate of 100 mm/yr is reasonable.

The recharge concentration for the model was set to 100 mg Cl/L. Most of the effluent waters will have higher Cl levels, but for purposes of modeling, we used 100 mg Cl/L as it can be equated to 100%. The results from the model can predict the relative degree of contamination outward from the source, i.e. 10%, 20%, etc. The recharge rate (100 mm/yr) and the recharge source concentration (100%) were applied to the model grid cells underlying the West and East Holding Ponds (see Figure 2).

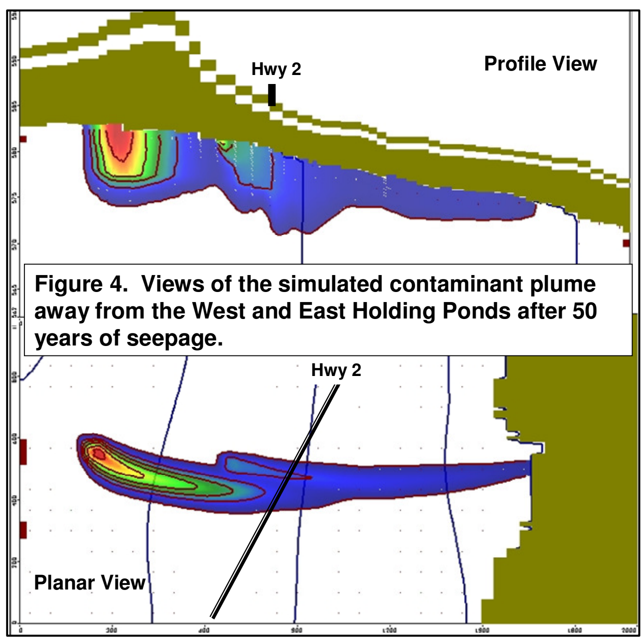


Figure 4. Views of the simulated contaminant plume away from the West and East Holding Ponds after 50 years of seepage.

A profile and planar view of the simulated contaminant plumes outward from the West and East Holding Ponds after 50 years is shown in Figure 4. Seepage from the West Pond had merged with the East Pond and the contaminant plume extended 1,700 m in the x-direction of the model domain, i.e. a travel distance of about 1000 m in 50 years.

The outer fringe of the plume was a dark blue color which is equivalent to 10% of the source concentration. The innermost brown-red color "circle" is equivalent to about 60% or more of the source concentration. The results indicate that there is sufficient groundwater flow intercepting the plumes to dilute the source concentrations. The results suggest that the local groundwater will not be "harmed" after 50 years of holding pond seepage. There are no domestic wells in the path of the contaminant plume and the bulk of the contaminant plume is diluted by local/regional groundwater flow to a value of about 10% of the source concentration.

Scenario 2: West Feedlot—Pit Lagoons

A diagram showing a planar overview of the north and south holding ponds and their respective drains is provided in Figure 5. The nature of the topography of the West Feedlot is such that the primary drainage will be southward and inward towards a low area where a deep holding pond (pit lagoon, 6 m deep) was constructed in 2005. However, because the north holding pond will not contain all the run-off water from a 24 hr-25 yr design storm with 100% runoff, we have added a second deep holding pond along the south edge of the feedlot (below the north holding pond). The north runoff containment pond is 5 m deep, 46 m wide (north-south) and 45 m long (east-west) at ground level. The bottom of the pit is 21 m wide and 35 m long. The north pond was designed to overflow into the south pond.

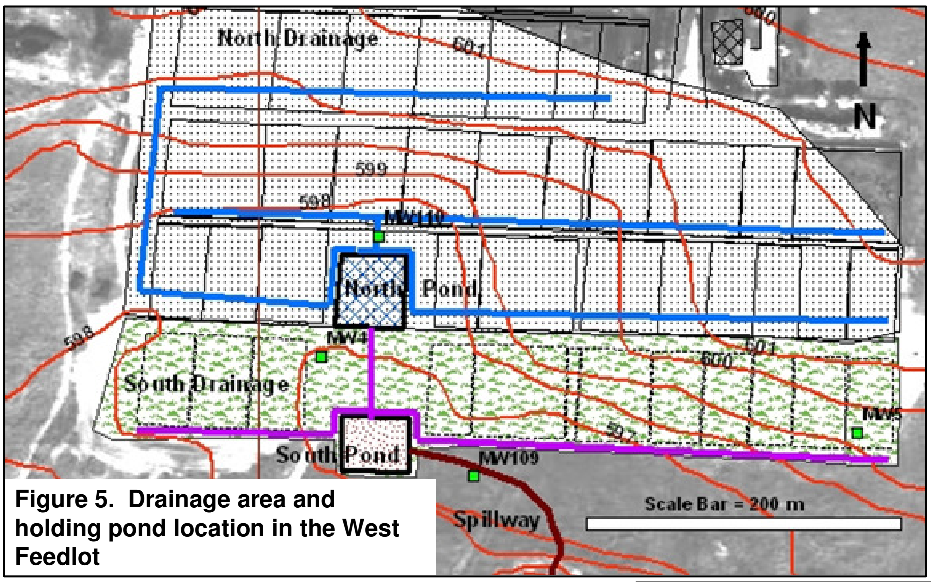


Figure 5. Drainage area and holding pond location in the West Feedlot

The south runoff containment pond is 5 m deep, 34 m wide (north-south) and 50 m long (east-west) at ground level (~595.2 m). The bottom of the pond is 9 m wide and 25 m long. The south containment lagoon (in conjunction with the north lagoon) was designed large enough to provide sufficient protection for the 100 year storm.

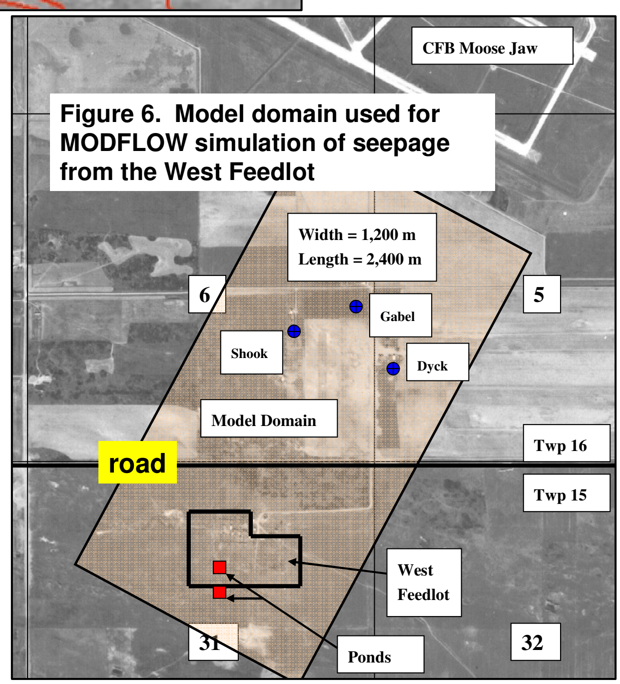


Figure 6. Model domain used for MODFLOW simulation of seepage from the West Feedlot

The "model domain" selected for this study was a rectangular shape 1,200 m wide and 2,400 m long starting on the south side of the West Feedlot and traversing across the road unto portions of Sections 5 and 6-16-26W2 upto the boundary of CFB Moose Jaw to the northeast in a downslope direction (see Figure 6). The X-Y grid spacing was 50 m by 50 m. Land elevations were extrapolated from the West Feedlot survey and from the topographic map for the land areas north and east of the feedlot.

Three layers were defined in the Z direction (vertical). The hydraulic conductivity estimates for the surface layer (about 14 m deep) were based on the soil measurements. The hydraulic conductivities assigned to the surface layer ranged from 3.6E-6 to 1E-5 m/sec (114 - 315 m/yr) in the horizontal directions (x and y) and Kx/10 in the vertical direction (z). The middle layer was also 14 m thick and was assigned hydraulic conductivity values of 1E-6 to 2.2E-6 (31.5 m 63 m/yr). This layer would have included more clays and silts and would be expected to have reduced K values. The bottom layer was located just above the aquifer. Because MODFLOW only allows one head to be simulated, we could not simulate the upward pressure head of aquifer. In order to get around this model quirk, we assigned the shallow (usually till) layer overlying the aquifer with a very low permeability so it could act as an aquitard to reduce upward movement from the aquifer. The aquitard horizontal K values were set to 1E-7 m/sec (3.15 m/yr) and the vertical K was set to 1E-9 m/sec (0.0315 m/yr).

Constant head levels were used to fix the upslope (west of the feedlot) and downslope (east of feedlot) boundary conditions. The west boundary heads were approximated from the measured depths to groundwater in the nearby monitoring wells and extrapolated to the boundary. Water table depths at the east boundary were set to 4-6 m as this water depth matched some of the domestic well data. Groundwater recharge was limited to the whole feedlot area. Based on the hydraulic conductivity measurements of the clay / silt layers underlying the holding ponds, it was calculated that a recharge rate of about 250 mm/year might be expected from each of the holding ponds. It is known that over time the pond bottoms would be sealed by fine organic and clay particles such that an hydraulic conductivity of 1E-8 m/sec or less could be achieved.

It was estimated that the feedlot as a whole was contributing to groundwater seepage and that feedlot seepage would amount to 25 mm/year over 50 years. It was estimated that the salt concentration in the seepage waters would be about 50% of the salt concentration in the collection pond waters. It is likely that during the early years, seepage beneath the feedlot pens would be higher than in later years. Over time, the feedlot surfaces become more compact and develop a slowly permeable organic layer. As a result. infiltration is reduced and denitrification of nitrate is enhanced.

The model simulation was run for a 50 year interval. The profile and planar view of the simulated contaminant plumes outward from the lagoons and feedlot is shown in Figure 7. The dark area on the centre-northwest side of the domain represents dry cells, i.e. the groundwater is below the layer we selected for viewing seepage. The most concentrated seepage appeared to be primarily downward and outward from the

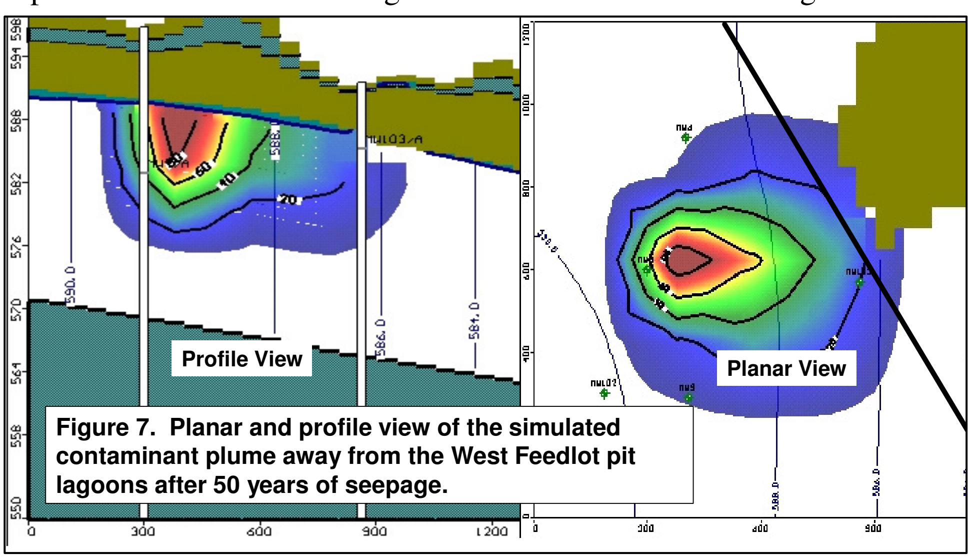


Figure 7. Planar and profile view of the simulated contaminant plume away from the West Feedlot pit lagoons after 50 years of seepage.

holding ponds. The outer fringe of the plume is denoted by a blue color, equivalent to less than 20% of the source concentration. The innermost brown-red color "circle" is equivalent to about 80% or more of the source concentration. The results indicate that there is sufficient dispersion and groundwater flow intercepting the plumes to dilute the source concentrations as it moves outward. The plume traveled less than 700 m in the x-direction of the model in 50 years. Overall, the outward movement of salts from the feedlot is slow mainly because of a low hydraulic gradient and the impediment of heavy lacustrine clays to the northeast.

There are three domestic wells (Shook, Gabel and Dyck) located downstream of the West Feedlot (see Figure 6). The 50-year model results indicate that none of these wells will be impacted by groundwater seepage from the West Feedlot. However, it is possible that at some point in the future (say, 200 to 300 years) the front edge of the contaminant plume could begin to reach the edge of the domestic wells.

Scenario 3: West Feedlot—Evaporation Pond

After the Scenario 2 study (Normac A.E.S. Ltd., 2008b), additional logs were obtained from the Saskatchewan Watershed Authority. The "new" logs were very valuable as they allowed us to more accurately formulate the local strata and fill in the missing gaps. As a result, the location of the surficial aquifer, i.e. Aquifer A in the Meneley (1975) report was more easily discernable. We were then able to show a linkage between the Aquifer A and the deeper semi-confined Aquifer B at one location (Figure 8). Previously, in the Main Feedlot report (Normac A.E.S. Ltd., 2008a), our focus was on the semi-confined Aquifer B from which most of the domestic wells withdraw water.

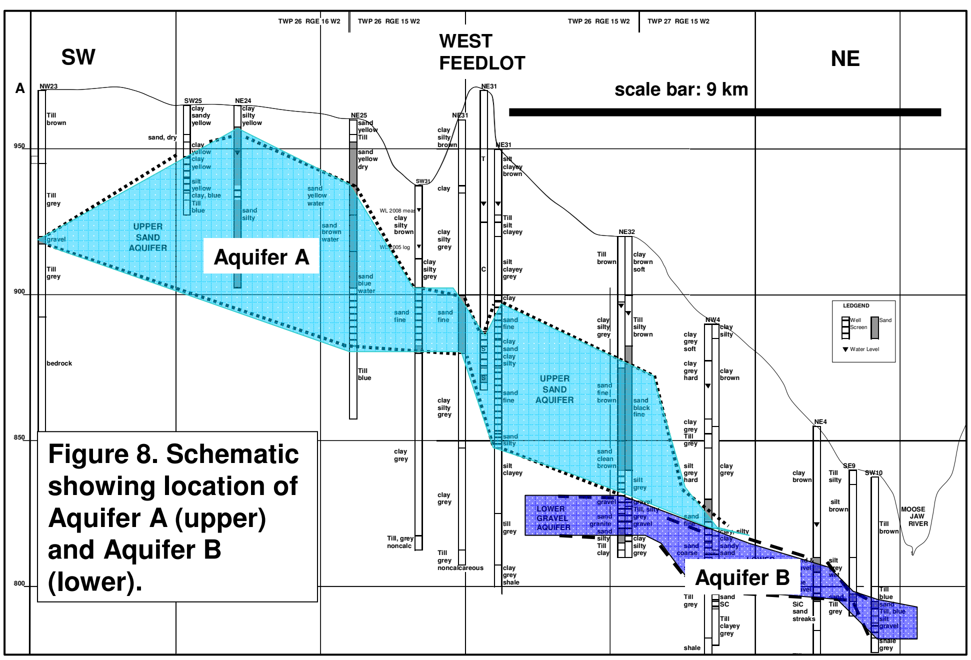


Figure 8. Schematic showing location of Aquifer A (upper) and Aquifer B (lower).

The ultimate goal of a feedlot design is to protect the aquifer. In light of the new aquifer information it was decided that the best approach would be to fill-in the existing pit lagoon and construct a much larger and shallower Evaporation Pond in the low trough south of the feedlot (Figure 9). Our intent was to reduce and/or eliminate seepage by spreading any runoff water over a large area so that it could readily be evaporated. In addition, the irrigation pump intake would be placed in a lower sump area designed so that we could effectively drain all the Evaporation Pond should we wish to do so. As with the previously proposed pit lagoons, the new shallow evaporation pond would have clay liner (see Figure 10). The compacted clay liner would be covered with 50 cm of silty loam soil to protect the layer from desiccation and physical harm. In addition, it was decided to allow the runoff water to spread and settle over the pond bottom from time to time so as to eventually provide a 15 cm layer of organic sludge. The organic fines connected with livestock waste and sludge also serve to reduce soil permeability by plugging small pores.

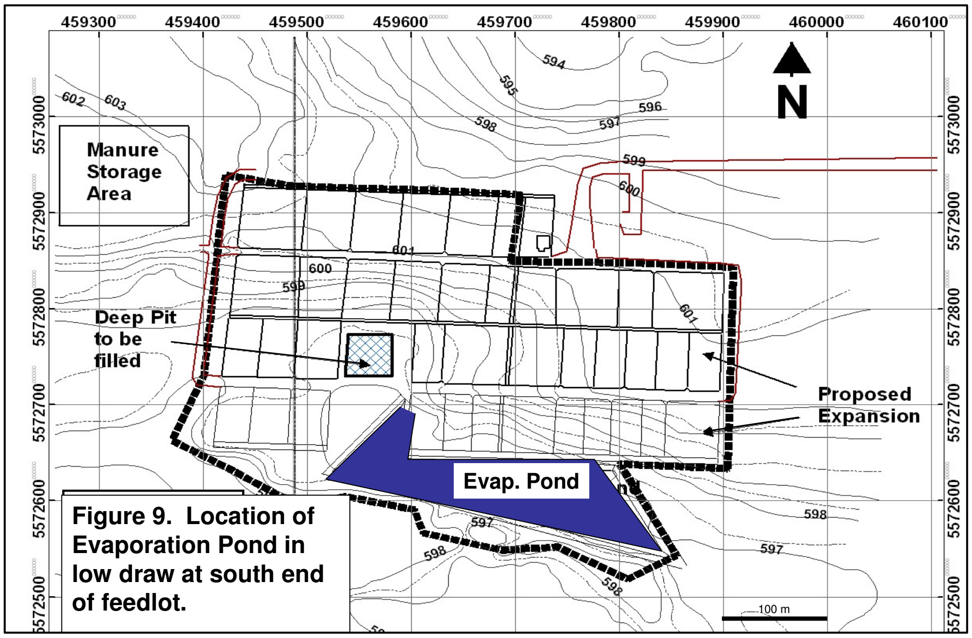


Figure 9. Location of Evaporation Pond in low draw at south end of feedlot.

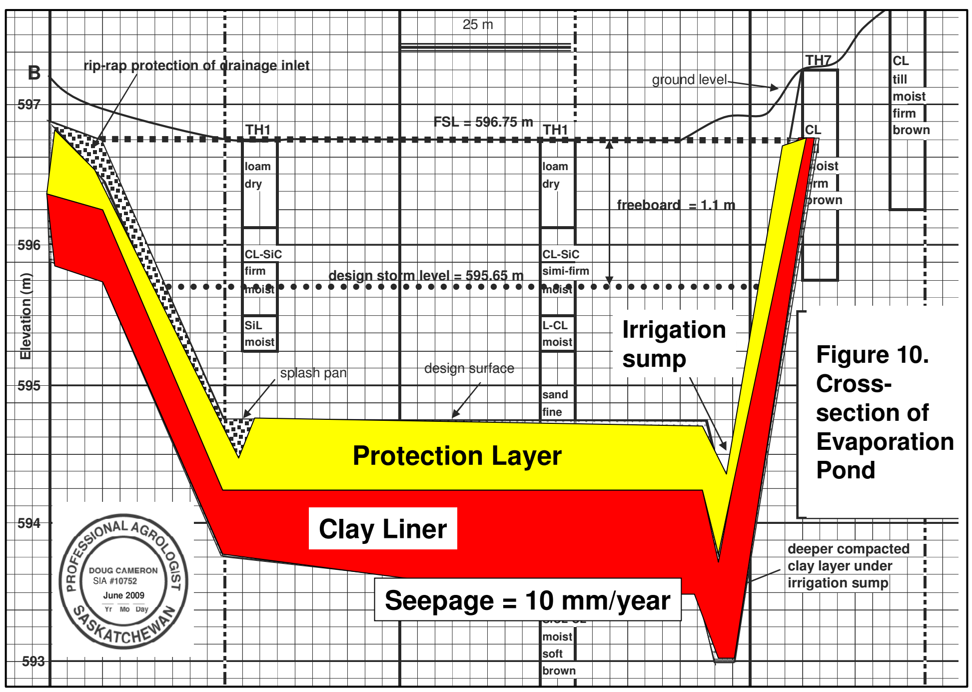
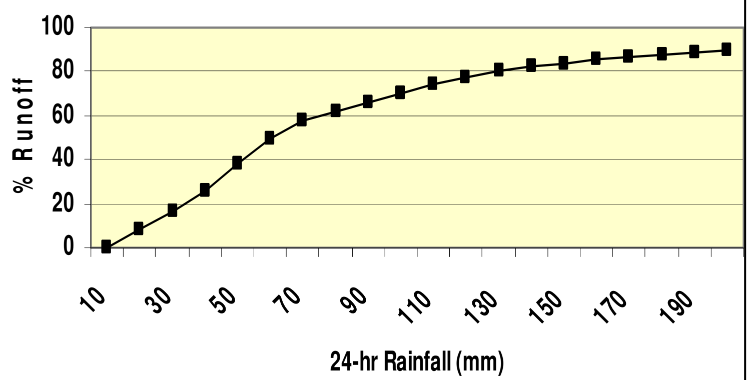


Figure 10. Cross-section of Evaporation Pond

Rainfall, Runoff & Evaporation Simulation— Maule and Fonstad (2007) have summarized much of the literature on runoff. Ultimately, they used Miller's runoff data from Lethbridge to develop a model for Saskatchewan. The literature observations were used to develop a relationship between the quantity of rainfall and the percent of rainfall that might contribute to runoff (Figure 11). The Moose Jaw daily rainfall/weather was available for 59 out of 66 years and was used to simulate runoff from the West Feedlot for each day for the period from April 1 until October 31 (214 days) of each year. Yearly evaporation was set near the climatic norm of 0.98 m/year and distributed over the months with peak evaporation occurring in July. When water levels in the Evaporation Pond exceeded 0.30 m, irrigation was started and 0.30 m of water was removed. The remaining water was left in the pond to evaporate. Zero-seepage was assumed.

Figure 11. Relationship between rainfall intensity (24-hr storm) and percent runoff.



Over the 59 years of rainfall at Moose Jaw, only two storms exceeded 71 mm, one on June 13, 1944 with 80.5 mm of precipitation (50 year storm) and one on August 13, 1999 with 88.6 mm.(100 year storm). On the average Moose Jaw receives 307 mm of precipitation from April 1 until October 31. The average annual accumulation of runoff water was 0.57 m of which about 80% was lost by evaporation and 20% was removed by irrigation. On the average, the pond bottom was wet 33.5% of the time. Irrigation was required in only 25% of the years.

Seepage below the Evaporation Pond—The vadose zone occurs above the water table and the soil pores are only partially filled with water. The design and operation of the Evaporation Pond at the West Feedlot is such that the soils under the EP will remain predominantly unsaturated and unsaturated flow is slow. In order to better predict downward movement of nitrogen and salts, a further simplification is required. One such simplification is to assume a steady downward flux under saturated conditions for at least part of the time. This type of simplification, then allows one to utilize analytical or mathematical solutions (equations that can generally be solved on a computer spreadsheet). One such equation was developed by Cameron and Klute (1977) for steady-state convective-dispersive solute transport with a adsorption-desorption. The Cameron and Klute (1977) equation can be simplified by removing the reversible first-order kinetic and the linear Freundlich isotherm equilibrium components and then solving the equation using the Ogata and Banks (1961) solution.

The thickness of the compacted clay layer will vary from 50 cm to 100 cm or more (average >60 cm) and the compacted clay layer will dictate the limiting permeability of the EP. The Ogata and Banks equation (Figure 12, upper graph) shows the 50% breakthrough (C/Co) at about 13 years. Once the contaminant reaches the top of the vadose zone (bottom of the clay liner), then it will infiltrate downward to the top of the saturated aquitard. The vadose zone is comprised of stratified lacustrine and sorted till materials. The breakthrough curve for saturated flow as predicted by the Ogata and Banks equation is provided in the lower graph in Figure 12 and shows that under continuous saturated conditions and with a unit hydraulic gradient, the concentration of the contaminant will be about 50% of the source concentration in about 6.5 years.

Thus, under saturated conditions, the Ogata and Banks equation would predict that the contaminant breakthrough from the bottom of the EP to the top of the water table would take about 20 years—13 years to seep through the clay liner and another 7 years to flow through the

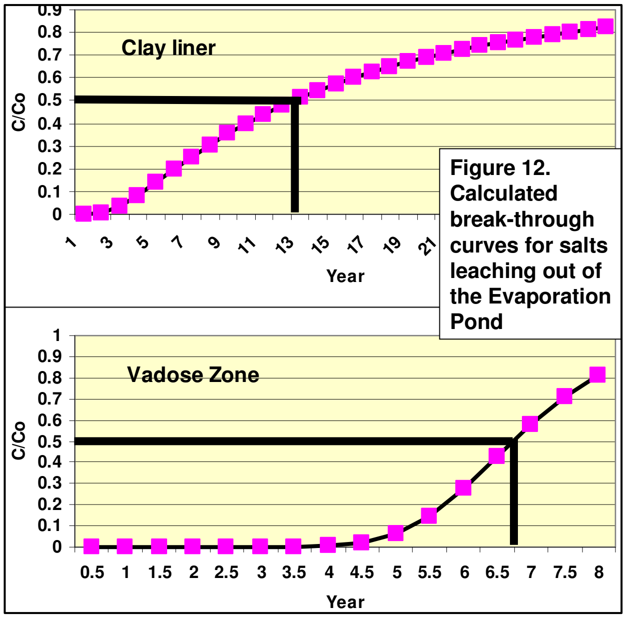


Figure 12. Calculated break-through curves for salts leaching out of the Evaporation Pond

vadose zone to reach the top of the saturated aquitard. However, on the average, saturated conditions only occur about 33% of the time during the April to October period (217 days) or about 20% of the time in 365 days. Under this scenario, it would take about five times as long (100 years) for the contaminants to seep from the Evaporation Pond to the top of the water table.

Model Results—Three layers were defined in the Z direction (vertical). The surface layer (about 4-6 m deep) was the dry vadose layer and was assigned decreasing hydraulic conductivities along the length of the model domain ranging from 8.0E-5 to 5E-5 cm/sec (25 – 16 m/yr) based on laboratory measurements for surface soils with bulk densities ranging from 1.26 to 1.34 g/cc. The second layer was about 9 m thick and would represent denser strata of mixed lacustrine and till soils above the aquifer. This layer was assigned hydraulic conductivity values of 4E-5 to 7E-6 cm/sec (12.6 m to 2.2 m/yr) with decreasing hydraulic conductivities in the horizontal direction and Kx/10 in the vertical direction. These conductivities fall within the range of hydraulic conductivities measured in the field. The third layer was about 6 m thick and would have included denser till clays and silts and would be expected to have reduced K values, decreasing over the length of the model domain. The lower layer was assigned hydraulic conductivity values of 1.5E-6 to 1E-7 cm/sec. This layer forms a cap over top of the aquifer.

The initial water table levels were extrapolated from the monitoring well data and boundary conditions to the whole "model domain". Groundwater recharge was limited to the Evaporation Pond (EP) and did not include the remainder of the feedlot. The compacted clay liner was designed to limit hydraulic conductivity to 0.01 m/year (10 mm/year, 3.2E-8 cm/sec). Thus, for the purposes of modeling, we used a recharge rate of 10 mm/year. The recharge concentration for the model was set to 100 mg Cl/L as it can be equated to 100%. Over the 100 year period of simulation, the total flux-in of water to the system was 19,310 m3, of which 65% was due to groundwater recharge from the EP. The water flux-out was 19,095 m3 for a gain of 205 m3 of water into the system amounting to a discrepancy 1.1%. Discrepancies under 5% are considered acceptable.

Profile and planar views of the simulated contaminant plumes outward from the EP after 200 years (100 years to reach water table and 100 years in contact with the saturated aquitard) are shown in Figure 13. The dark gold area in the centre of the domain represents dry cells, i.e. the groundwater is below the layer we selected for viewing seepage. The most concentrated seepage appeared to be uniformly downward and outward from the EP. The outer fringe of the plume is denoted by a blue color, equivalent to less than 20% of the source concentration. The innermost yellow color "ellipsoid" is equivalent to about 80% or less of the source concentration. The

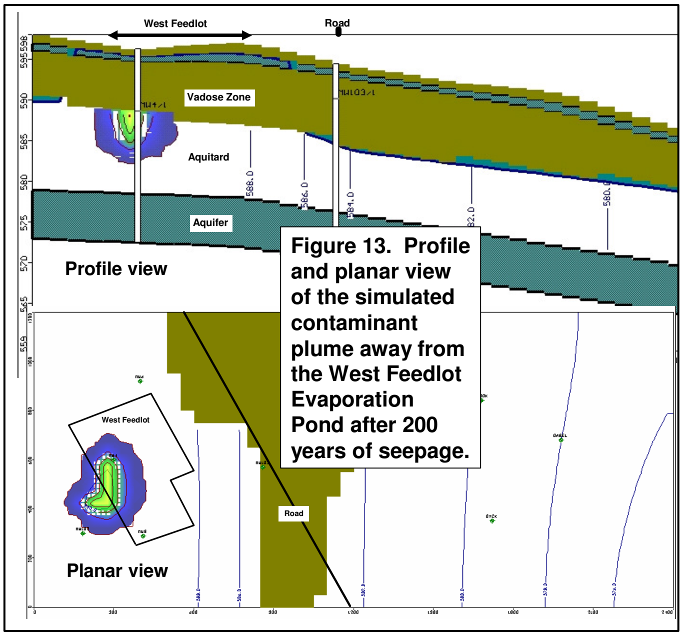


Figure 13. Profile and planar view of the simulated contaminant plume away from the West Feedlot Evaporation Pond after 200 years of seepage.

results indicate that there is sufficient dispersion and groundwater flow intercepting the plume to dilute the source concentrations as it moves outward and downward.

Over time, the lateral and vertical movement of the plume appeared to expand relatively uniformly in all directions and after 100 years, the leading edges of the plume traversed about 100 to 150 m outward from the edge of the EP. Overall, the outward movement of salts from the feedlot EP was slow, mainly because of a low hydraulic gradient and the impediment of the mixed stratified lacustrine-till clays to the northeast. There are three domestic wells (Shook, Gabel and Dyck) located downstream of the West Feedlot. The model results indicate that none of these wells will be impacted by groundwater seepage from the West Feedlot.

Summary and Conclusions:

MODFLOW was used as modeling tool to predict salt movement under three different types of feedlot waste storage ponds: a typical shallow holding pond with a clay liner, a deep unlined pit lagoon, and a shallow evaporation pond with a compacted clay liner. In the situation of the typical holding pond at the Main Feedlot, the model predicted that the chemical plume will travel about 1000 m in 50 years. The vertical seepage of the plume was about 10 m and the plume does not reach the “target” aquifer at a depth of 30 m. Most of the movement is lateral. After 50 years, the chemical concentration 100 m outward from the holding pond was less than 10% of the source concentration. Seepage from the holding ponds is sufficiently slow so that incoming groundwater dilutes much of the pollution.

At the West Feedlot, the model predicted that after 50 years, lateral seepage from the deep pit lagoons reached about 600 m along the hydraulic gradient to the northeast. The hydraulic gradients near the West Feedlot were not as steep as at the Main Feedlot resulting in a reduced lateral flow. However, because of the proximity of the underlying aquifer (20 m deep) and the location of 3 domestic wells downslope, it was decided that a different design was required to protect the target aquifer and reduce lateral movement.

The design selected was an evaporation pond which would reduce the level of ponded water by increasing evaporation, construction of a compacted clay liner at the bottom of the evaporation to reduce infiltration, construction of a silty loam protective cover to prevent desiccation and cracking of the clay layer, and irrigation to remove any ponded water in the evaporation pond to reduce seepage.

Under saturated conditions, it was calculated that the chemical seepage plume would reach the underlying water table in about 20 years. However, since the bottom of the evaporation pond is only wet 20% of the time, then saturated flow would occur only on a sporadic basis and it is more likely that it may take 100 years for the contaminant front to reach the top of the saturated aquitard. The model predicted that after 100 years of seepage in the saturated zone, lateral movement amounted to 150 m outward (concentric) and downward seepage was about 6 m.

In conclusion, evaporation structures appear to be a viable alternative to holding ponds for reduction of downward contaminant seepage and protection of the aquifer.

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